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# Short-period temperature oscillations in the vicinity of Monterey Bay.

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# SHORT-PERIOD TEMPERATURE OSCILLATIONS IN THE VICINITY OF MONTEREY BAY

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Robert H. Miller

SHORT-PERIOD TEMPERATURE OSCILLATIONS

IN THE VICINITY OF MONTEREY BAY

by

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

United States Naval Postgraduate School
Monterey, California

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This work is accepted as fulfilling

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ABSTRACT

The naval importance of knowledge of short-period variations in ocean thermal structure is exemplified by the effect of internal waves upon underwater sound propagation patterns.  This thesis describes an investigation undertaken to examine some of the characteristics of short-period (.071-.01 cycles/sec) variations of thermal structure in the vicinity of Monterey Bay.  Time series bathythermograph observations at 7.0 minutes' interval and to ten hours duration were collected at a position in 65 fathoms near the shoulder of the Monterey submarine canyon.  The depths of one-half degree Fahrenheit isotherms were analyzed for power spectral distribution, and comparison of the individual time-series' spectra was made.  Variance of depth of selected isotherms over 140-minute intervals was compared with tidal phase, showing maximums of variation occurring immediately after tidal extremes.  A comparison was drawn between spectral analysis of data obtained from a thermistor temperature sensor suspended in the water beneath a pier in Monterey Harbor.  Internal wave-like characteristics are recognizable, though conclusive evidence of the existence of internal waves cannot be shown from the data collected.

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## 1. Introduction

Much effort has been directed toward the description and prediction of the long-period variations in ocean thermal structure for the purpose of estimating variations in underwater sound propagation velocity. Methods of predicting characteristics of the thermocline, to which many sonars are sensitive, have been developed and tested (Tabata [13] , Laevastu [12] ). The usefulness of such techniques is limited, however, in that they provide, at best, an estimate of mean characteristics about which some variation can be described. These authors suggest that a portion of the variation can be explained as the effect of internal waves.

Lee [8] has shown a dramatic example of the calculated sound re-fraction, and the resultant varying-intensity sound energy field, due to the presence of idealized high-frequency internal waves representative of those observed in nearshore areas off San Diego. It is clear, from his example, with its areas of marked intensification and attenuation, that the effect of internal waves is more complex than a uniform change or variation in thermocline depth. Additionally, it is apparent that the single bathythermogram cannot truly describe the thermal structure of a vicinity, in that the nature of <u>variability</u> is not indicated. Thus, there seems ample justification for the pursuit of more knowledge of the short-period variations in thermal structure, ultimately, of course, for the evaluation of their effect upon sonar detection range. This project was undertaken to provide a description of some such thermal structure variations.

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2. Program Objectives and Description

   a. Objectives

   The project was planned as an investigation of short-period oscillations of internal temperature structure in the vicinity of Monterey Bay, hopefully to show the existence of internal waves and to describe their characteristics. To this end, simultaneous observations of subsurface temperature variation were planned at two sites, one off-shore using a bathythermograph, the other nearshore, employing two existing thermistor temperature sensors with recorders installed on Wharf II in Monterey Harbor. The nearshore site was not ideally located for observation of internal waves progressing from offshore; however, the spectral distribution of the variations observable from the pier would be of interest. It was intended that several time-series would be collected, each of duration (approximately) of the tidal period. The several series were to be collected during tides of various magnitudes so that some evidence of the effect of tidal current variations upon internal wave generation might be noticed.

   Observation of a deep scattering layer, if any appeared, was planned to determine the effect, if any, of short period thermal variations upon its depth.

   b. Observation site selection

   (1) Offshore location

   The offshore location (figure 1) was selected, at a position approximately 36°40'N, 122°00'W (292T/3¼ miles from the Pt. Pinos buoy), after consideration of several factors, including evidence of both temporal and horizontal variation of vertical thermal structure.
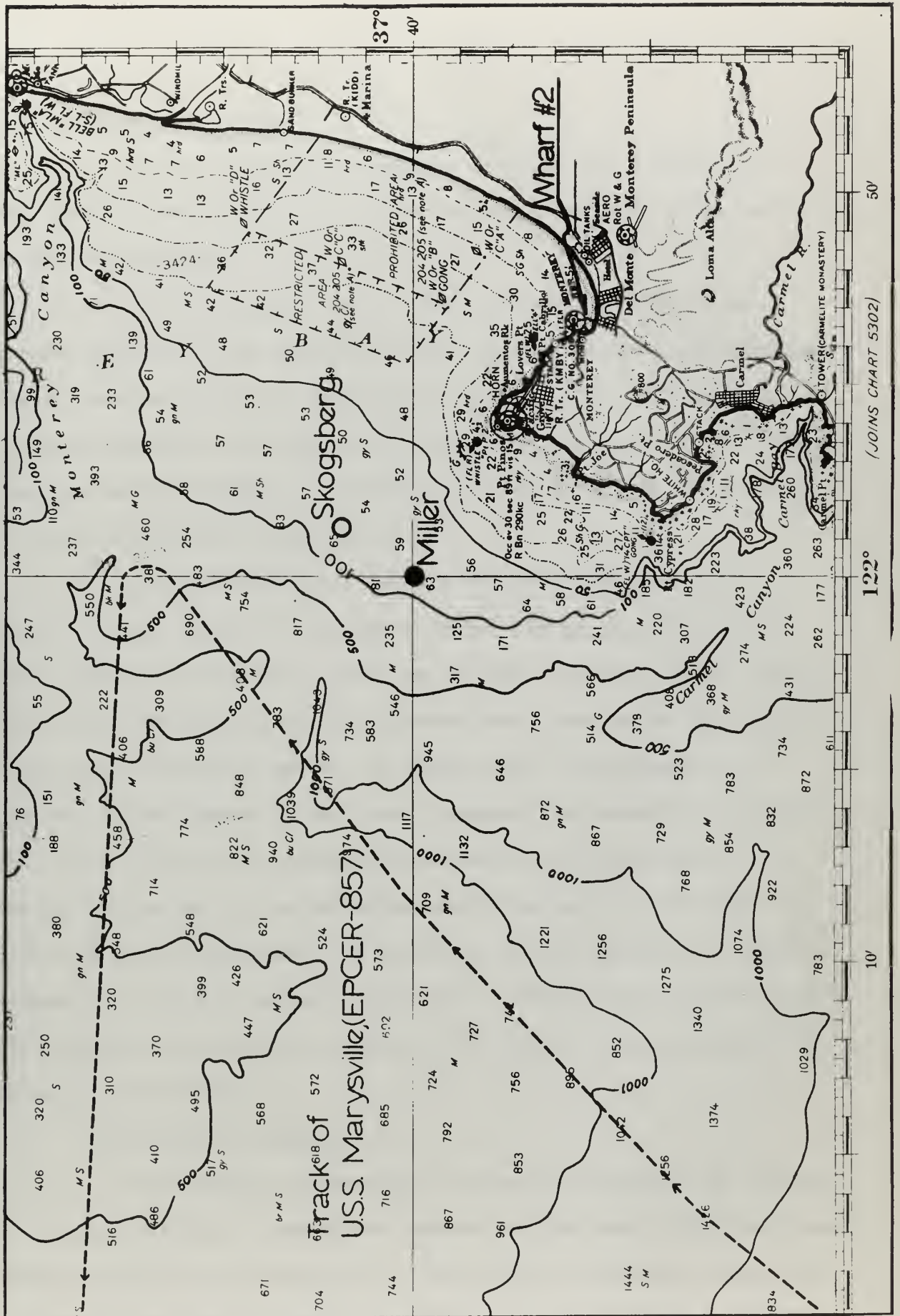
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FIGURE 1

Figure 1

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The considerations follow:

(a) It was near the position selected that Skogsberg [1] was unable to duplicate temperature measurements at depth within periods as short as one hour.

(b) In July 1962 the USS Marysville (EPCER-857) towed a thermistor chain in the vicinity of the location selected, and recorded (record courtesy of Dr. G. H. Jung) variations in depth of isotherms ranging from 30 ft. in relatively steep gradients, to over 100 ft. where gradients were not severe. "Apparent wavelengths" ranged from 1/8 mile to three or more miles respectively.

(c) In that several authors (Davis and Patterson [10] , Lee [9] ) have suggested in theory or shown through observations and model studies that internal waves may be formed as tidal currents flow over bottom discontinuities, the site was positioned on the shoulder of the Monterey submarine canyon. The water depth is approximately 65 fathoms, and the bottom slopes steeply seaward, but gradually shoreward. The bottom contours are somewhat convex seaward, so may provide convergent refraction of internal waves moving shoreward to the site. The bottom is sufficiently level, at the site, so that likelihood of anchor movement on slopes is reduced. The water is sufficiently shallow so that the entire water column was subject to observation with reasonably high frequency of BT drops.

(2) Nearshore Location

The nearshore observation site was determined by the location of existing thermistor temperature sensors located beneath the Wharfinger's Office on Wharf II in Monterey Bay. The progress of internal waves from the seaward observation position involves refraction through a minimum

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of 50°-60°, (see figure 1) and travel-distance a minimum of seven miles.

  c. Equipment and Procedures

    The offshore observations were conducted from the U. S. Naval Postgraduate School Oceanographic Research Vessel (63 ft.), using a 450 ft. BT with gold-wash BT slides. The boat navigated to within ½ mile of the selected site at 65 fathoms where a taut-line moored marker buoy was then fixed. Position of the boat was maintained, using engines, by visual reference to the marker buoy. Several visual and radar fixes during each observation period assured no drift of the marker.

    (1) Stationing

      The taut-line moored marker was employed since no anchoring gear available was satisfactory for anchoring the boat. The moored float rig was designed, with reference to Isaacs, et al [4] , to mark the anchor position to within 100-ft. radius. It consisted of a scrap iron anchor in an "H" form weighing approximately 120 pounds in air, 1/8 inch diameter (No. 4) braided nylon mooring line, and a float constructed of a commercially available 13-gallon capacity plastic carboy. The marker buoy was placed on station immediately prior to each observation period. When fathometer-indicated depth reached 65 fathoms during the approach to station, the boat was stopped and the marker-buoy anchor lowered to the bottom using the nylon line over a gypsy-head on the winch. The boat was maneuvered to the anchor position using "wire-angle" as a guide, and the nylon line hauled in by hand until more than 30 pounds (estimated) of tension had been established. The float was then tied on and allowed to drift free of the boat, marking the anchor position.

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An alternate method of lowering the anchor was used for
safety, particularly, in adverse seas.  A one-inch manila line was
used to lower the anchor to the bottom, while the nylon line attached
to the anchor was paid out slack to avoid damage and strain.  Once
bottomed, the anchor was raised approximately ten feet from the bottom,
the nylon line was tensioned as before, by hand, and the float attached.
The anchor was then lowered once again with the marker float in the
water.  When the marker float was observed to be operating satisfactorily,
its draft a rough indication of sufficient tension in the mooring line,
the manila lifting line, with ample slack, was attached to a second
supporting float consisting of three plastic one-gallon Clorox bottles,
and allowed to drift free for use later during recovery.  The manila
lifting line, thus supported, provided little if any lifting force on
the anchor and insufficient dragging force to move the anchor.

The No. 4 nylon provided sufficient margin of strength for
the operation, yet was sufficiently elastic through the range of loads
imposed by surface waves, wind and current, to maintain nearly constant
tension.  It cannot endure much abrasion damage, however, and care was
taken in handling.

Station-keeping required that the helm be manned constantly,
and difficulty varied considerably depending upon wind and swell relative
direction and intensity.  Long period waves (swell) to eight feet, and
winds to approximately 18 knots were limiting maximums.  In general,
station was maintained to within 100 yards, usually to within 100 ft.
of the marker.  When swell and wind direction were nearly constant during
an observation period (the usual situation) the direction of error from

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on-station varied little. The buoy was kept "close on the bow", and the bow headed constantly into the wind, which supplied the major drifting force.

(2) Bathythermograph Employment

Once position had been established, BT drops were commenced at seven-minute intervals, and continued until the practical limit of endurance, equipment breakdown, or adverse weather conditions. The interval was established after determining through brief experimentation that good BT traces were obtained when a raising/lowering rate of 50 meters/minute was used. At this rate, neither "double-traces" due to lag of the BT mechanism during stationary dropping nor "stepping" due to static friction effects were noted. The gold-wash BT slides exhibited a tendency to flake, occasionally, necessitating cleaning of the stylus after each drop to remove residue which might produce a wide trace on subsequent slides. A controlled hydrographic winch with "meter-wheel" was used to provide the selected lowering/raising rate. A 150-pound weight was suspended ten feet beneath the BT to provide stability and to aid in making drops vertical. The seven-minute data interval allowed sufficient time between drops for changing slides, cleaning stylus, and allowing at least 30 seconds of soaking to stabilize the BT at the surface prior to each drop.

(3) Miscellaneous

Occasional observations of "bucket temperature", wind, wave conditions, and cloud cover were recorded during each period. Several measurements of salinity, conductivity, and temperature were attempted at 50 ft. depth intervals to 300 ft. using an Industrial Instruments, Inc.

RS5-3, Portable (induction) Salinometer. However, operation was not entirely satisfactory, and depth of sensor impossible of accurate determination due to streaming in relative currents; hence, data obtained were not reliable.

(4) Nearshore Observations

Temperature variation with time was measured by two thermistor temperature sensors, with appropriate amplifiers, and two Varian pen recorders operating with paper speed of one inch/hour. Full-scale deflection of the record was 5°C on five-inch recording paper. The sensors were suspended from Wharf II in Monterey Harbor in 28 feet of water at nominal depths of eight feet and 15 feet, which varied as water level did. Maintenance difficulties prevailed in all but one offshore observation period when a satisfactory record was obtained during a period of 18 hours and 40 minutes, but lagging the offshore observations by about nine hours.

(5) Data processing

The BT slides were viewed through a standard handheld magnifying viewer and depths of occurrence of each ½F noted. When double-tracing occurred, the depth selected was the arithmetic mean of the two depths of crossing. A wide section in a portion of the trace was treated as incipient double trace. When a wide trace appeared throughout the BT slide record, it was generally interpreted as due to debris on the BT stylus, and the center of the trace was estimated as the correct indication. These procedures provided data generally of very good continuity when integrated with the rest of the series. (The author personally handled all BT drops and extracted all data, so

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consistency of procedure and accuracy of data transcription is believed

good). It should be noted that accuracy of interpretation varied as the

temperature gradient, less depth accuracy possible when gradient was

"weak". In general, independent reinterpretation of selected BT traces

produced data within three feet of the original estimate.

All data were then plotted as isotherm depth versus

time to check apparent continuity and reasonability of the time series

data accumulated. Thus checked, the data of each isotherm were pro-

cessed for power spectral estimates on a Control Data 1604 computer

using the BIMD-35 (Power Spectral Analysis) Program, one of a series of

programs compiled by the University of California, Los Angeles, Division

of Biostatistics, Department of Public Medicine and Health, School of

Medicine. The program was employed in several ways, i.e., using

various prewhitening constants, removal of linear trend and using

various numbers of lags in order to gain experience. The analysis used

to gain the results presented, however, is without prewhitening or

detrending, and employs arbitrarily selected numbers of lags.

Data[1] taken at Wharf II, the nearshore site, were

not plotted in raw form, since the recorder trace offered the visual

information necessary for estimating the validity of the data. Tempera-

ture was read from the trace at seven-minute intervals and placed on cards

for computer processing in the same manner as the offshore data for com-

parison of spectral distribution with that estimated from the appropriate

data collected offshore.

[1]Instrumentation on Wharf II supplied under research grant to U. S.
Naval Postgraduate School by the Office of Naval Research.

3. Description of data

    BT data were collected on seven occasions at the designated site.
Four of the sequences obtained were long enough to warrant spectral
analysis. The longest of the three rejected extended only three hours.
BT slides and numerical data extracted from all of the sequences are in
the files of the Department of Meteorology and Oceanography, U. S. Naval
Postgraduate School. This section describes the four significant
sequences and the conditions surrounding their collection. The data
are plotted in raw form as $\frac{1}{2}$F isotherm depths versus time of observation.

    Some of the series indicate isotherm oscillations of relatively
large magnitude where temperature gradients are weak. It should be
noted that error of interpretation and of the instrument is magnified
in this sort of presentation when the gradient is weak. The BT trace
may contact the temperature index line for 50 feet or more of depth and
estimates of the exact depth of crossing become poor.

    There are some series of oscillations which are described by only
one data point per extreme. One might suspect instrumentation noise
since the wave period is twice the observation interval. It can be noted
in some of these incidents, however, that the isotherms at other depths
are progressing smoothly in longer period oscillations, so support is
lent to the credence of data at all levels.

    To evaluate the effect of positioning error upon the significance
of data, assuming that it represents internal waves, some wave lengths
were calculated. A constant density gradient was assumed since a marked
thermocline does not exist in most instances observed. Salinity and

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temperature data collected allowed calculation of an approximate density

gradient of -3.6 x $10^{-5}$ g/cm$^3$/m. The wavelength for this condition

is given by the formulas:

$$c_n = \frac{\sigma}{k_n} \doteq \frac{h}{n\,\pi} \sqrt{N^2 - \sigma^2} \qquad (3.01)$$

$$L = \frac{2\pi}{\sigma} c_n \qquad (3.02)$$

where:

n = mode, an integer

$c_n$ = phase speed

$\sigma = \dfrac{2\pi}{T}$ = angular frequency

h = water depth

L = wave length

$N \doteq \sqrt{-\dfrac{g}{\rho}\dfrac{\partial p}{\partial z}} \doteq$ Väisällä's frequency

The wave length of the shortest waves observable (.071 cpm) from the

data is greater than 540 meters, assuming a mode-1 oscillation (a maximum

of vertical velocity occurring at only one level in the water column.)

The variance of position was generally less than one quarter the wave-

length of the shortest observable feature.
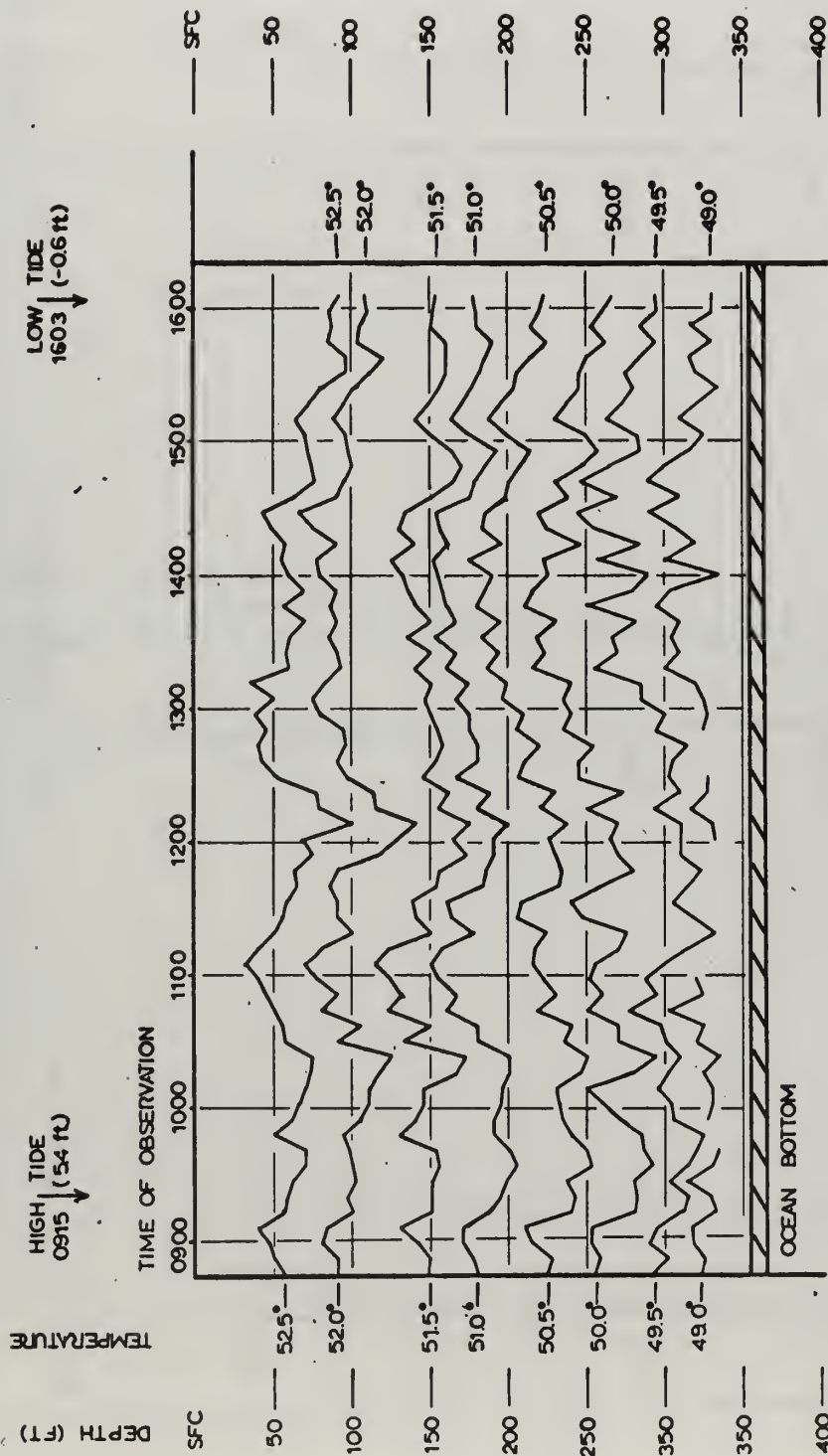
a. Data collected 16 March 1965

The following describes conditions surrounding the collection of the raw data plotted on figure 2:

| | |
|---|---|
| Position | 36°40.15'N |
| | 121°59.80'W |
| Depth of bottom | 59 fathoms |
| Time between BT drops | Seven minutes |
| Times of observation | 0845-1606 PST |
| Length of observation period | 7 hours, 21 minutes |
| Number of data | 64 points |
| Wind condition | 210°/6 kt. |
| Estimated swell | 270°/3-4 ft. |
| Sky conditions | Overcast with occasional brief breaks (ten minutes maximum). |

Tides                    Low 0346 PST/1.5 ft.

                                                      (Range +3.9 ft.)

                         High 0915 PST/5.4 ft.

                                                      (Range -6.0 ft.)

                         Low 1603 PST/-0.6 ft.

                                                      (Range +5.5 ft.)

                         High 2221 PST/4.9 ft.

Comments:

A typical BT trace, figure 3, shows no marked thermocline. Some double tracing of the BT occurred, especially near mid-depth and during the latter 2½ hours of the sequence. The lack of sunshine during the day is reflected in little warming indicated, the near surface isotherm trending downward only slightly during the period.
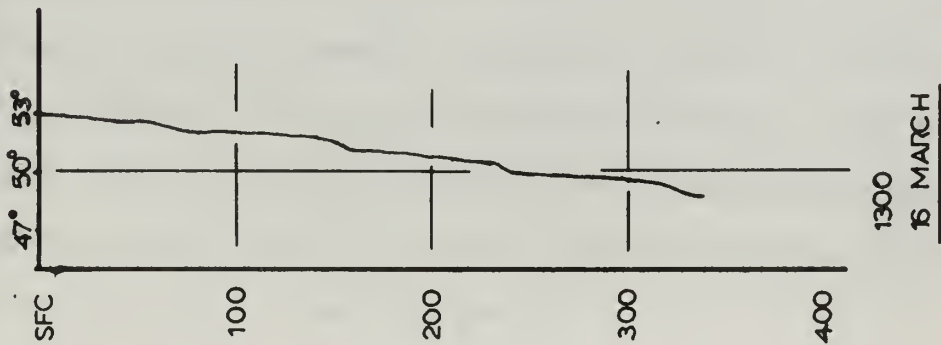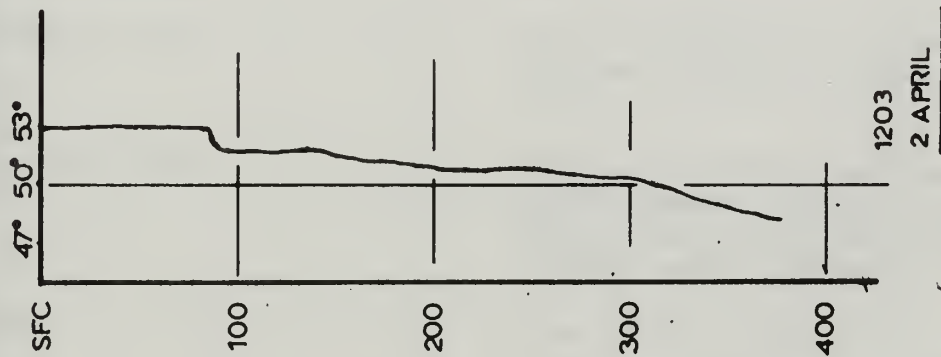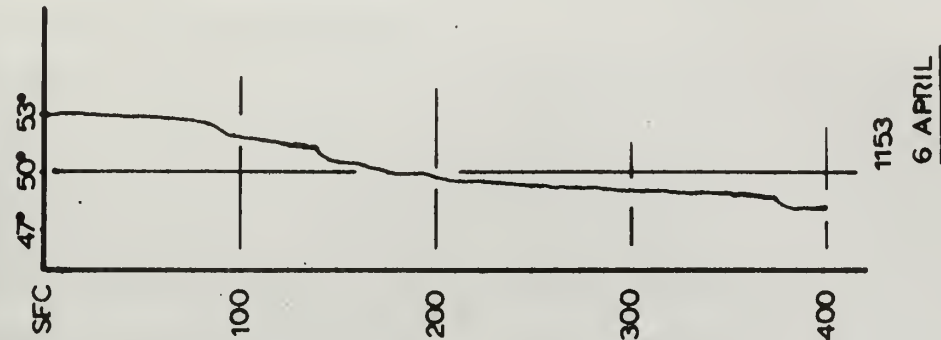
Density calculations from salinity data collected at several depths between the surface and 250 feet, indicates density gradient of approximately $-3.6 \times 10^{-5}$ g/cm$^3$/meter. This value is an estimate only, since the data are not accurate.

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Depth of Isotherms vs. Time

16 March 1965

Figure 2

Figure 2

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Typical 'BT' Traces

FIGURE 3

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b.  Data collected 26 March 1965

      The following describes conditions surrounding collection of the data plotted on figure 4:

| | |
|---|---|
| Position | 36°40.20'N |
| | 122°00.05'W |
| Depth of bottom | 65 fathoms |
| Time interval of BT | Seven minutes |
| Times of observation period | 0744-1753 PST |
| Length of observation period | 10 hours, 9 minutes |
| Number of data | 88 points |
| Wind condition | Calm |
| Estimated swell | Initially 280°/3 ft., 6 second period 1600 PST 280°/2-3 ft., 10-13 second period |
| Sky conditions | Overcast initially, with occasional light showers.  Clouds thin and broken during early afternoon, then thin overcast after 1530 PST |
| Tides | High 0507 PST/4.0 ft. |
| | (Range -3.8 ft.) |
| | Low 1231 PST/0.2 ft. |
| | (Range +3.6 ft.) |
| | High 1927 PST/3.8 ft. |

Comments:

The thermocline which was observed early in the period at about 75 ft. persisted through the morning, appeared to separate into two "steps" by early afternoon, and dissipated entirely by the end of the series.  Many double traces of the BT were noted, some in the region of the thermocline, suggesting oscillations with periods less than sampling interval.  A typical BT trace is shown on figure 5.
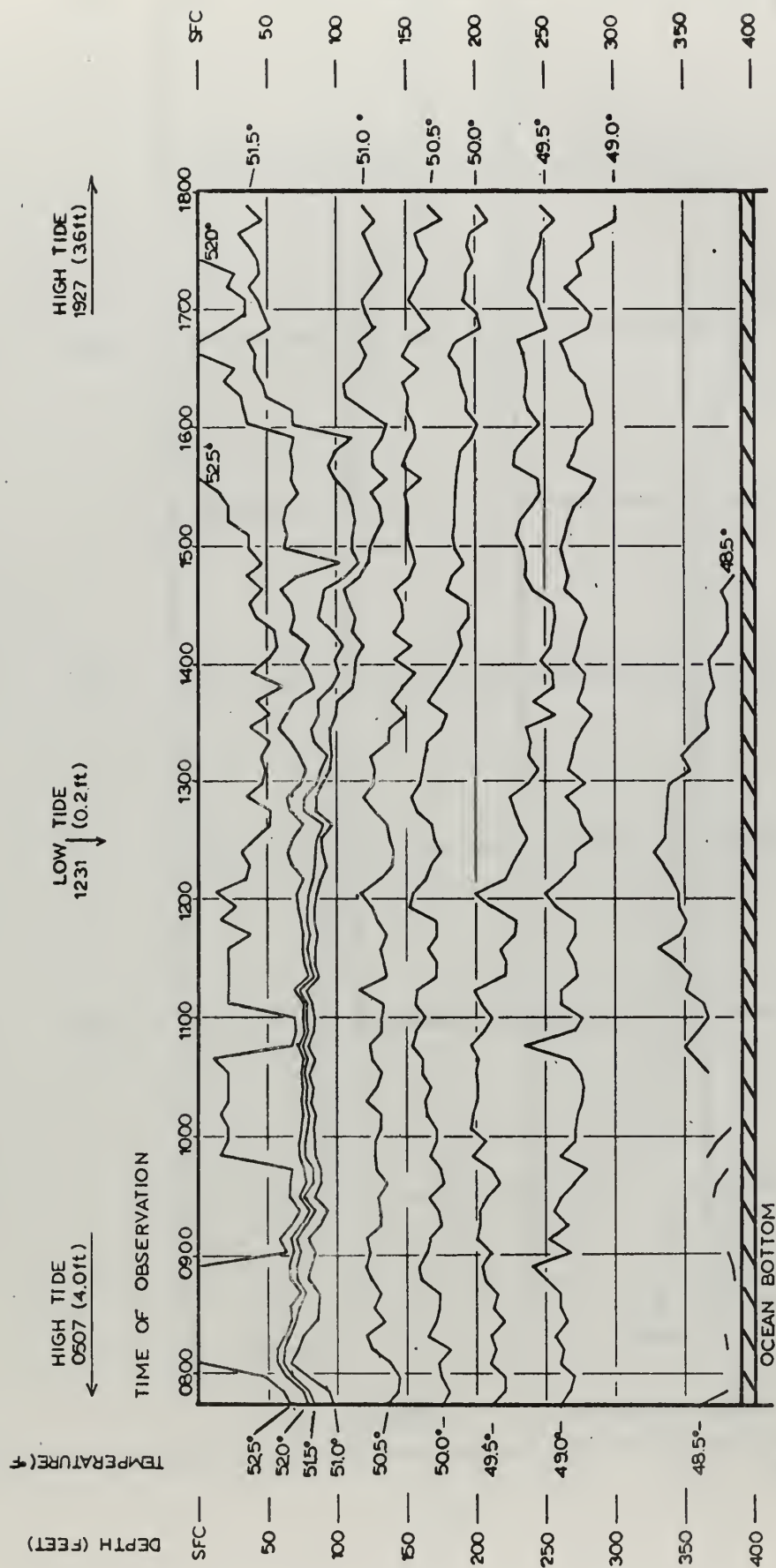
Depth of Isotherms vs. Time

26 MARCH 1965

Figure 4

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BT TRACES    26 MARCH 1965
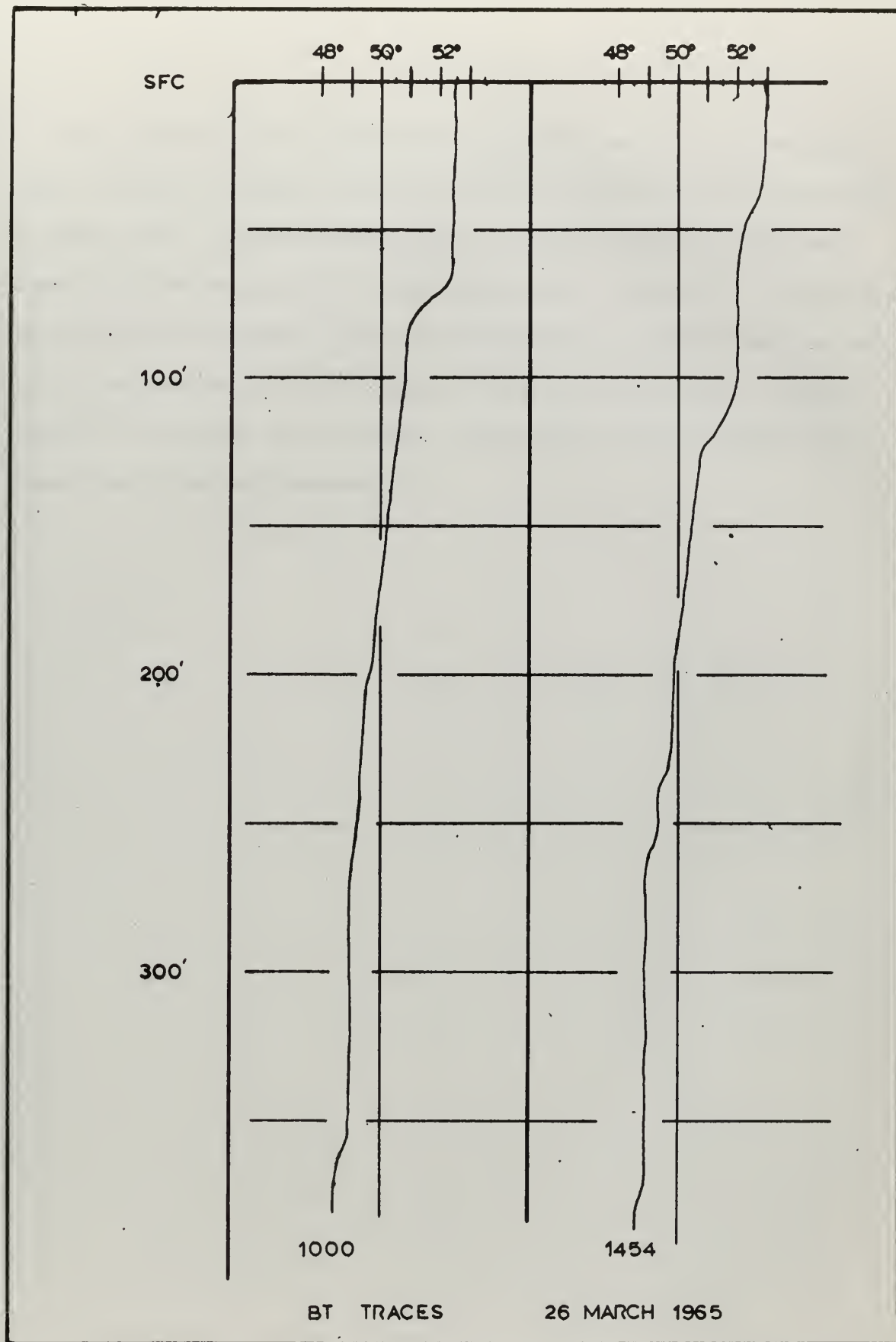
FIGURE  5

Data were collected at Wharf II during this period, but the useful record obtained extended only from 1600 PST, 26 March 1965, to 1040 PST, 27 March 1965. The temperature record obtained from the 8-feet deep sensor appeared reasonable, with a temperature range of $2^{\circ}C$. The 15-feet deep sensor is believed to have been operating, but the record indicates only slow temperature drift through a range less than 0.25C. The pier record is not shown, but its power spectrum has been calculated (8 ft. sensor only) and is discussed later.

c. Data collected 2 April 1965

The following describes conditions surrounding collection of
the data plotted on figure 6:

| | |
|---|---|
| Position | 36°40.20'N |
| | 122°00.05'W |
| Depth of bottom | 63 fathoms |
| Time interval of BT | Seven minutes |
| Time of observation period | 0744-1828 PST |
| Length of observation period | 10 hours, 44 minutes |
| Number of data | 93 points |
| Wind condition | Calm (NW) |
| Estimated swell | Initially 3 ft/10 sec/280°T<br>1030 PST 6 ft/10 sec/280°T<br>Decreased slowly thereafter |
| Sky conditions | Occasional brief sun through breaks in thin overcast.  Several short periods of drizzle until early afternoon when clouds became scattered (.5 cover) |
| Tides | Low 0438 PST/0.5 ft. |
| | (Range 3.8) |
| | High 1042 PST/4.3 ft. |
| | (Range -3.3) |
| | Low 1644 PST/1.0 ft. |
| | (Range 3.8) |
| | High 2243 PST/4.8 ft. |

Comments:

Transient thermoclines appeared and disappeared during period.  Double
tracing was common, especially during the last several hours of the
sequence.  Minor inversions and inversion tendencies appeared, often
accompanied by double traces.  A typical BT trace is plotted on
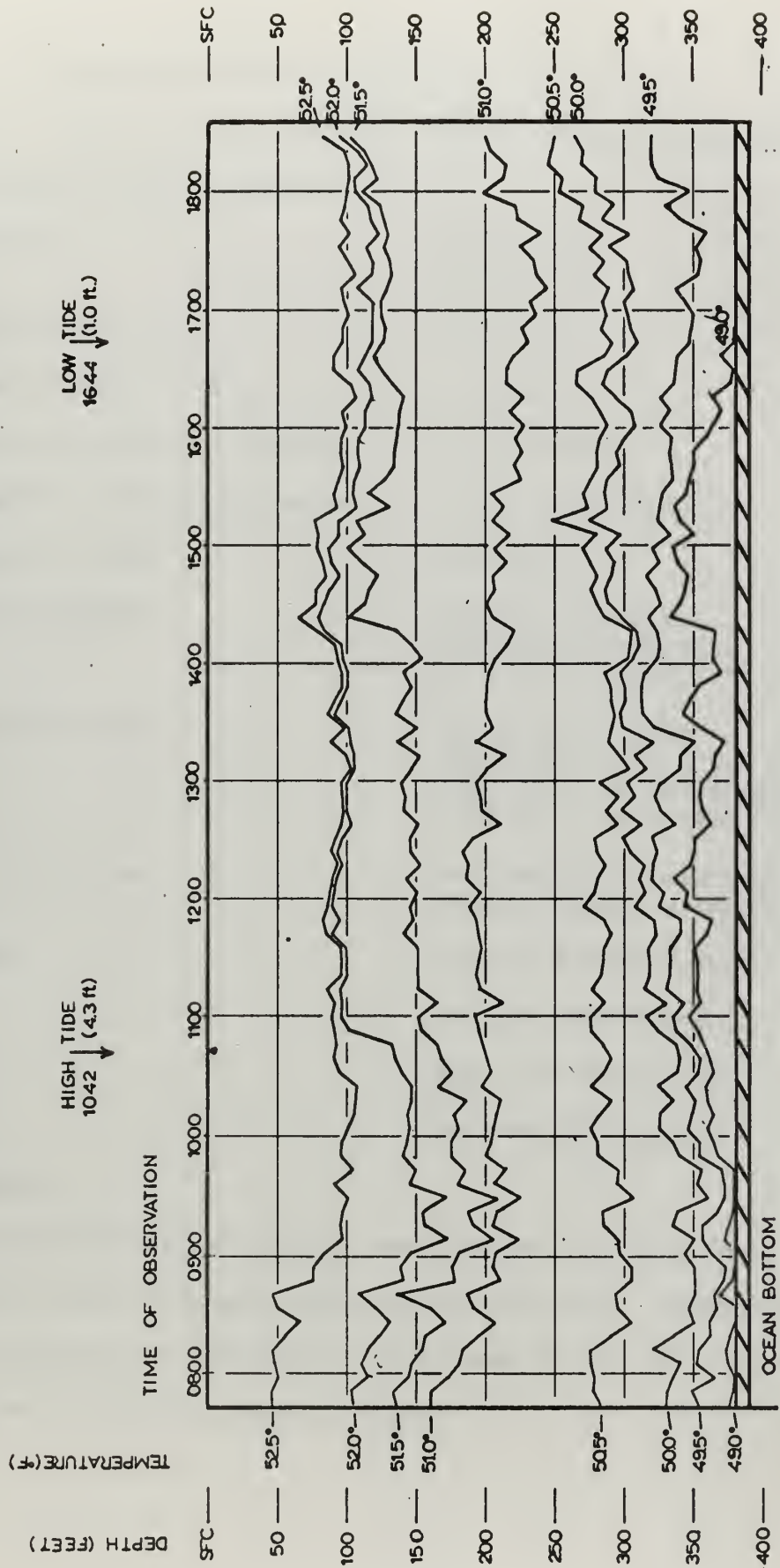figure 3.

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Depth of Isotherms vs TIME
2 April 1965

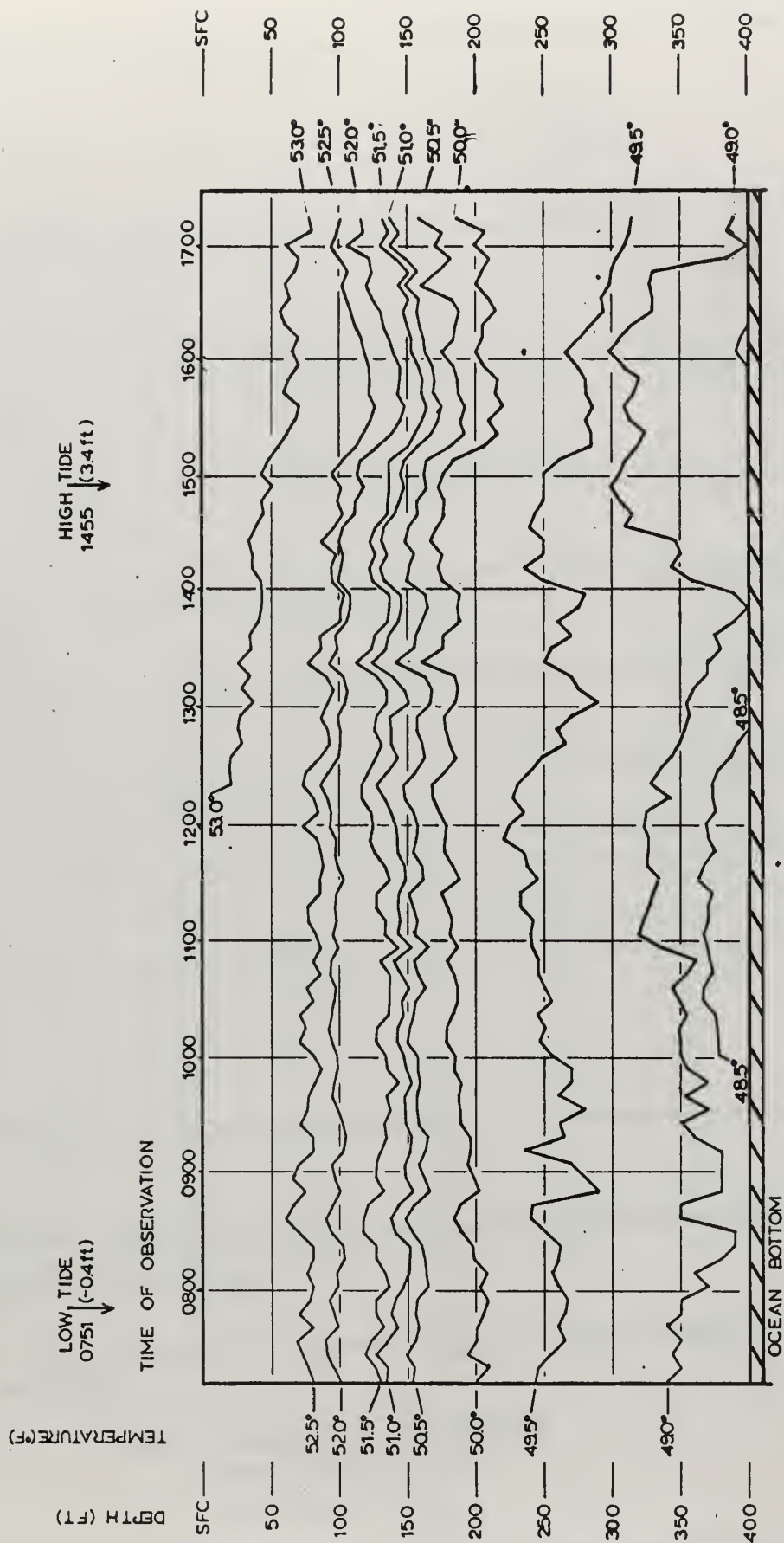Figure 6

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d. Data collected 6 April 1965

The following describes conditions surrounding collection of the data plotted on figure 7:

| | |
|---|---|
| Position | 36°40.23'N<br>121°59.50'W |
| Depth of bottom | 66 fathoms |
| Time interval of BT | 7 minutes |
| Time of observation period | 0713-1715 PST |
| Length of observation period | 10 hours, 2 minutes |
| Number of data | 87 points |
| Wind condition | Initially 280°T/3 kt.<br>1100 PST - 285°T/8 kt.<br>1300 PST - 290°T/15 kt. |
| Estimated swell | Initially 2 ft/280°<br>0933 PST - occl. 5 ft. swell<br>1200 PST - 1-2 ft. wind waves on swell<br>1500 PST - sea 310T/7 ft. |
| Sky conditions | Overcast with occasional breaks during morning, thinning during afternoon |
| Tides | High 0013 PST/1.9 ft.<br>(Range -5.3 ft.)<br>Low 0751 PST/-0.4 ft.<br>(Range 3.8 ft.)<br>High 1455 PST/3.4 ft.<br>(Range -.6 ft.)<br>Low 1922 PST/2.8 ft. |

Comments:

Many small transient features were observed on the traces. Though double traces occurred, they were not prevalent. Surface warming during the afternoon is indicated by down trend of near surface isotherms. Typical BT trace is shown on figure 3.

Depth of Isotherms vs Time
6 APRIL 1965

Figure 7

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Power Spectra of Isotherms
PLOTTED AT
MEDIAN DEPTH OF ISOTHERM

16 March 1965

FIGURE 8

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Power Spectra of Isotherms
PLOTTED AT
MEDIAN DEPTH OF ISOTHERM
26 March 1965

FIGURE 9

Power Spectra of Isotherms
PLOTTED AT
MEDIAN DEPTH OF ISOTHERM

2 April 1965

FIGURE 10

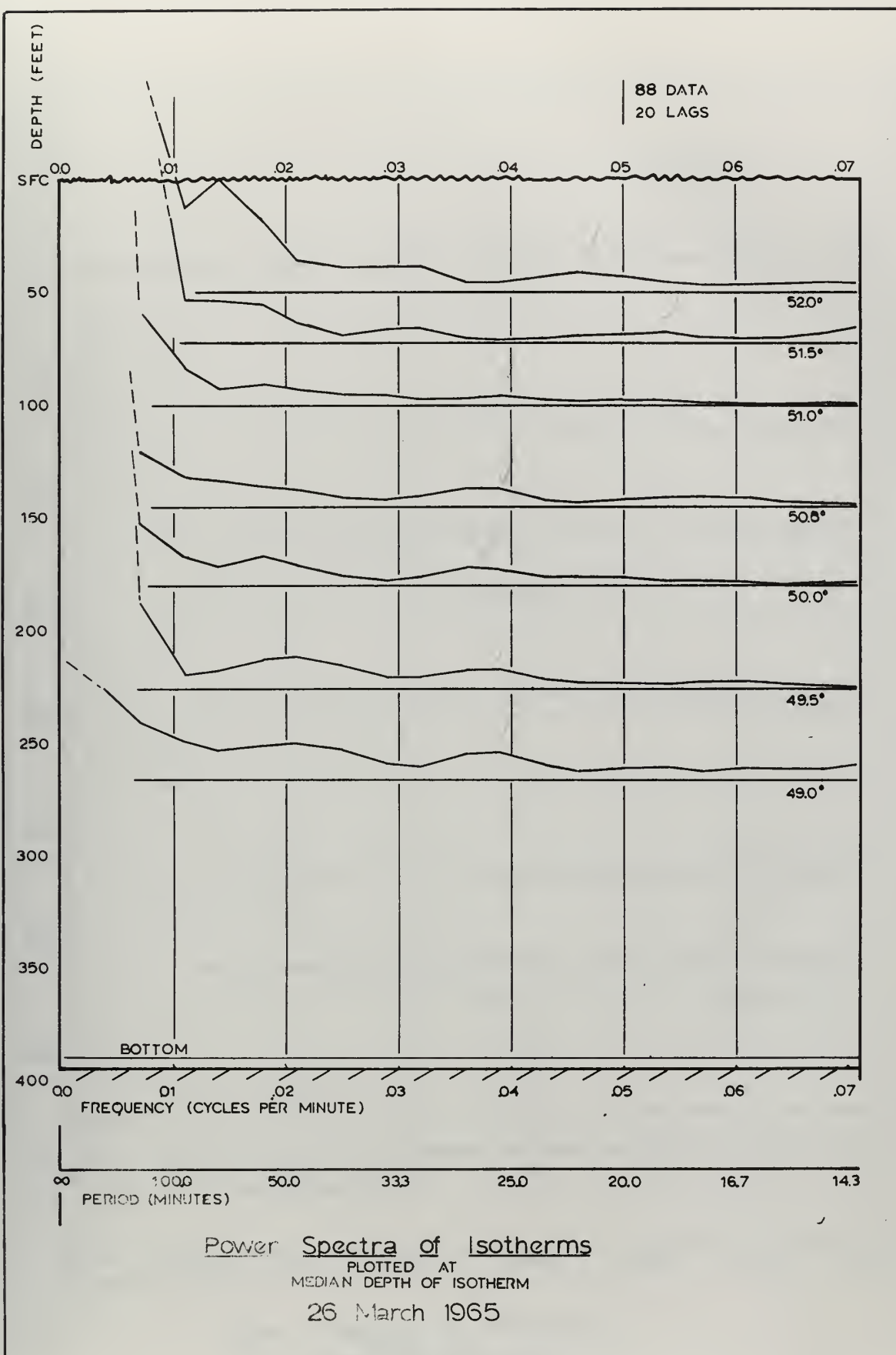Power Spectra of Isotherms
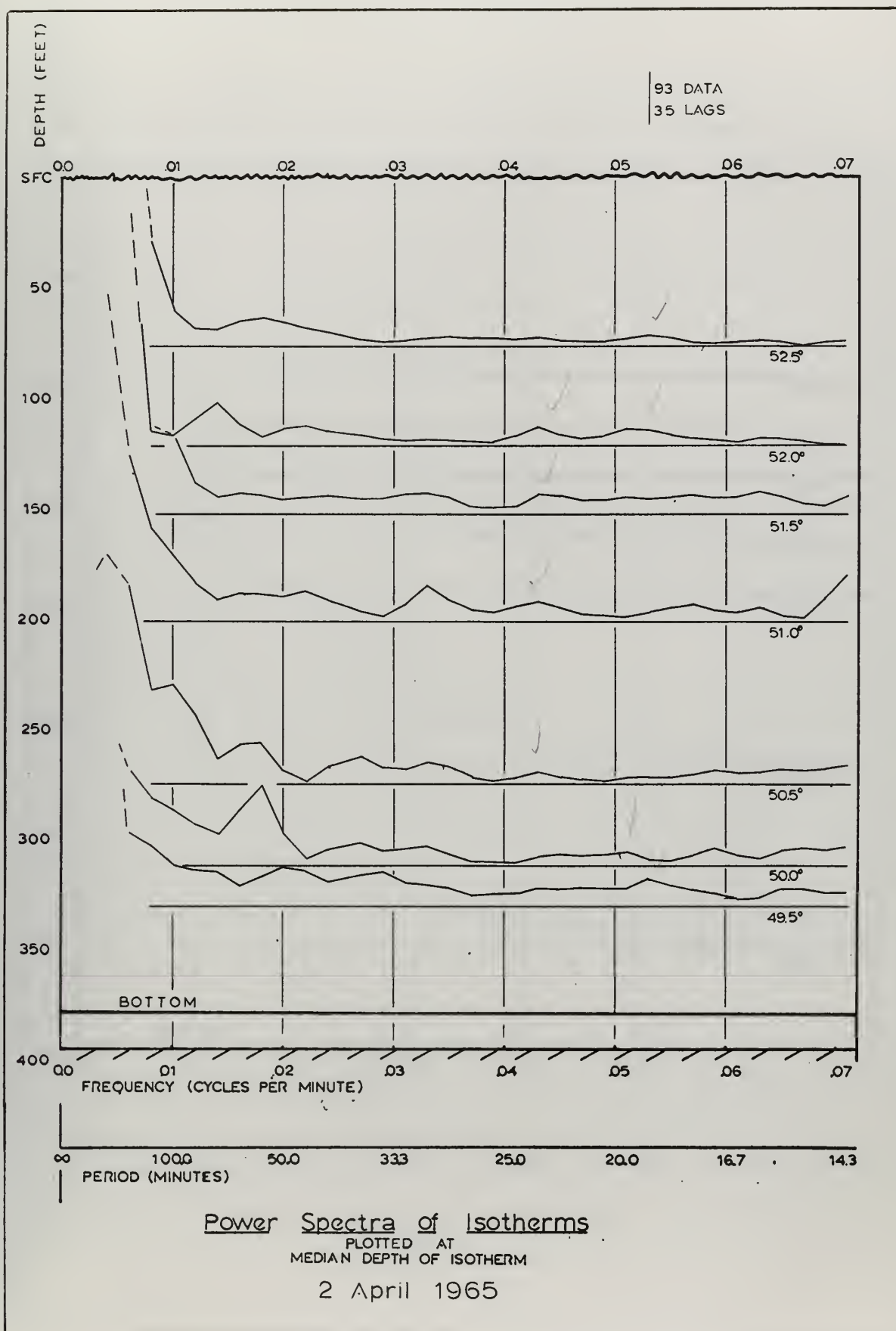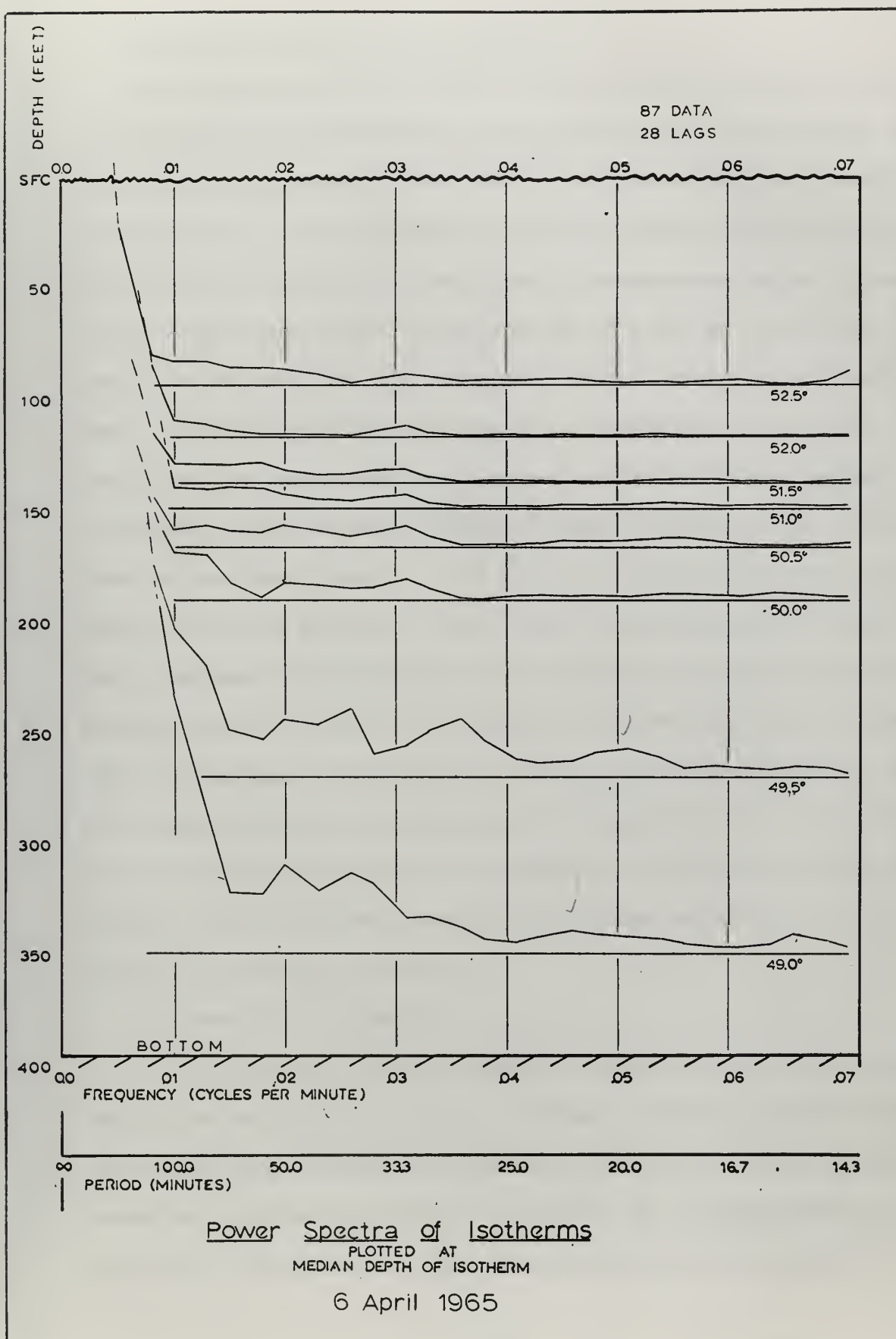PLOTTED AT
MEDIAN DEPTH OF ISOTHERM

6 April 1965

FIGURE 11

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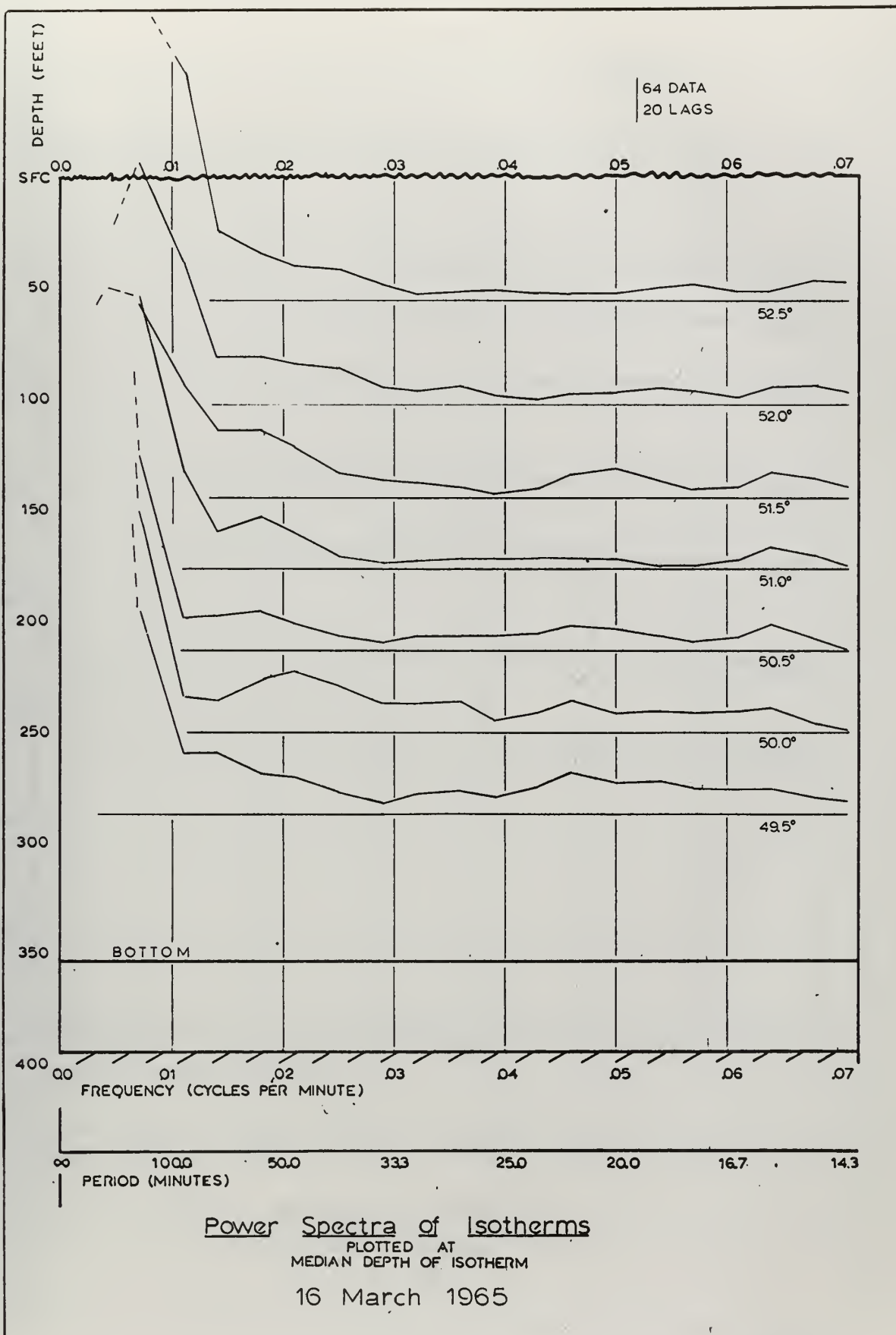
## 4. Discussion of Analysis and Results

The observed variation in depth of isotherms is treated in parts of this discussion as though due in significant part to the vertical movement of water in internal waves, during which water-particle temperature is conserved. It is recognized that other effects, not easily isolated, may be present also, as the advection of inhomogeneous water, convective and current-driven eddies, turbulence due to wind and wave action, radiative and molecular heat exchange, chemical reactions and sampling error. Suspicion that internal waves are responsible for a large portion of the temperature oscillation is enhanced by the _apparent_ coherence in phase between isotherms through a major portion of the water column (see figures 2, 4, 6 & 7). It is more difficult to assign the cause of such activity, that is oscillations apparently random in period and amplitude yet coherent in large vertical extent, to other phenomena such as eddies. (If coherence were notable in all isotherms, then misplacement of the slide in either the bathythermograph or on the viewing grid could be responsible.) Regardless of which phenomenon it is that contributes most to the observed fluctuation, the spectral analysis can provide some insight regarding the variability of thermal structure as observed by the BT.

### a. Power Spectrum Analysis

The results of the power spectrum analysis of isotherm oscillations are on figures 8 thru 11. The spectra of continuous $\frac{1}{2}°F$ isotherms from each observation period were plotted in an array ordered according to the median depths of isotherms, so a rough impression can be gained of the position in the water column which each spectrum

describes. The power spectrum estimates were computed employing various numbers of lags. (See Appendix I ). The number of lags employed for the calculation of the spectra presented is noted on each of the figures. The number of lags chosen exceeds the 5%-10% of the record recommended by Blackman and Tukey (see Jenkins [7] ) as the appropriate truncation point. Lags used, rather, comprise 25% to in one case 38% of the length of the record. The resultant power spectrum, even with such a large number of lags, appears quite smooth and exhibits characteristics much like the spectra calculated with fewer lags. This is apparently a reasonable result since, as suggested by Jenkins, truncation points may be much larger than those suggested by Tukey if the autocovariance function converges to negligibly small values at greater lags. It does become small (less than 10% of zero lag auto-covariance) in several of the series analyzed with 35 lags. No attempt, however, has been made in this project to optimize the spectral analysis through selection of various lags as Jenkins proposes. More meaningful results could be described were such techniques employed.

The presence of long-period oscillations presents a problem in the analysis. The data records are shorter than the period of low frequency harmonics which can be observed in the raw data plots. These long period contributors may be of tidal period or local inertial period (10.04 hrs.). Such an effect interferes with the estimation of the spectrum at other frequencies so that removal of long-period influence by "detrending" may be of some help. Detrending was employed experimentally; but, again, negative spectral estimates were sometimes obtained (see Appendix I ), so computations were made without detrending. A better solution would be

precise removal of the long period oscillation, using a best-fit sinusoid determined from a longer series of data with appropriate smoothing.

A visual comparison of area under the power curves suggests that more energetic oscillations occurred during the period of largest tidal range. Maxima and minima of power apparent on the curves cannot, in most cases, be shown statistically significant with 90% confidence by the chi-square test (Panofsky [11] ). However, some of the power extremes are supported by the appearance of similar features in the power spectra at several adjacent levels in the array. By adding the area under all the isotherm spectrum curves of all four observation periods by 0.01-cycle/minute bands, it is shown in figure 12 that the mean power spectrum is a smooth one with no frequencies apparently favored. The maxima indicated in the arrays of individual isotherm spectra, then, are either the result of sampling fluctuations or of internal wave spectral distributions peculiar to the conditions during the observation period, but none are permanent features of the mean smoothed power spectrum.

Estimates of power spectra are, in general, associated with the assumption that the time series represents a stationary process. In this application, the power spectrum is used to describe short-period oscillations, which may be internal waves, suspected of formation in some way associated with tidal phenomena. The tides, however, do not represent a steady-state process; so the assumption cannot be satisfied, except approximately, for short segments of the tidal cycle; and, un- fortunately, the spectrum cannot be found accurately and with definition
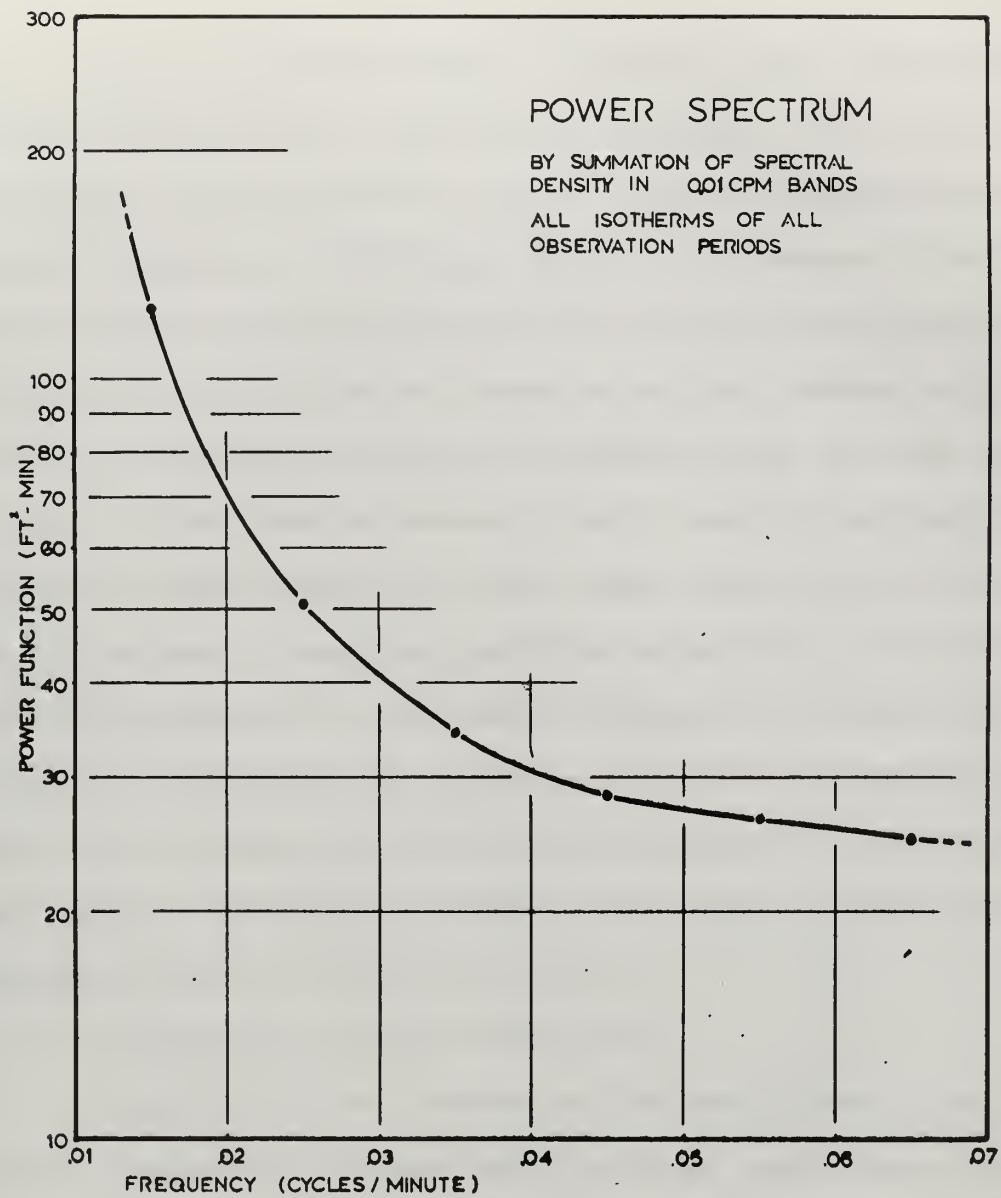
POWER SPECTRUM

BY SUMMATION OF SPECTRAL
DENSITY IN 0.01 CPM BANDS

ALL ISOTHERMS OF ALL
OBSERVATION PERIODS

FIGURE 12

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from a segment of short duration. In addition to the effect of con-
tinuous variation of the suspected exciting agency, the effect of in-
ternal waves near the period of the tide tends to interfere with esti-
mation of the power in the higher frequencies of interest. Long records
permit better estimates of the mean power spectrum during the interval;
but, if the record includes all stages of the tide, nothing can be learned
about the relationship between high frequency energy and tidal stage.
Perhaps with many shorter segments of data, carefully selected with
regard to similar conditions of tidal phase, amplitude, and water
physical structure, some more significant relationship could be de-
termined by application of the ergodic theorem (see Davenport and Root [5] ).
At any rate, optimizing the techniques of spectral analysis for ex-
ploratory investigation of relationships between tidal activity and
high frequency internal wave activity would require  mathematical
treatment beyond the scope of this project.

    b.   Indications of Modes of Oscillation

        Examination of the isotherm oscillations (figures 2, 4, 6 & 7)
reveals a suggestion of higher than first-order oscillations in some
regions; but, since a spectrum of frequencies contributes to the oscil-
lations observed in the raw data, clear evidence of higher modes is not
present. A continuous distribution of density with depth is suggested
by the data collected. Internal waves, therefore, are likely to exist
in a variety of modes of oscillation (Defant [6] ). The first mode of
oscillation is that in which vertical displacement, or vertical velocity,
is in the same direction throughout the water column, with the maximum
occurring at one depth. Second mode describes opposite directions of

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motion in upper and lower portions with two maxima of amplitudes; third phase has three maxima, etc.

The power spectra (figures 8 thru 11) may also be examined for suggestions of higher modes of oscillation. The spectral distribution represents an indication of the contribution to total variance by oscillations in particular frequency bands. A comparison of the magnitude of the power function in a particular frequency band at various levels in the water column, then, suggests levels at which the variance, or the amplitude of vertical isotherm movement, is greater. These may also be interpreted as levels of antinodes, indicating the mode of oscillation present. There are some instances of maxima of the power function at more than one level in the arrays of power spectra, as near .018 cycles/minute on figure 11. This might imply energy in a higher mode; but again the evidence is not conclusive. Sampling error cannot confidently be discounted as the cause for apparent spectral maxima. Additionally, if the process is non-stationary, then oscillation in a particular mode of a particular frequency may be unlikely to persist throughout the observation period.

c. Tidal Phase Relationship with Isotherm Variance

A gross indication of internal wave activity relative to the phase of the surface tide wave is shown on figure 13. The variances of 20-point segments of the data (about each 20-point mean) were calculated for two isotherms from each of the four observation periods. Isotherms chosen were those nearest depths of 100 feet and 200 feet. In most cases, the magnitude of variance appeared greatest in the segments of data which represent the period immediately following the tidal extremes.

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ISOTHERM VARIANCE RELATED TO TIDAL PHASE
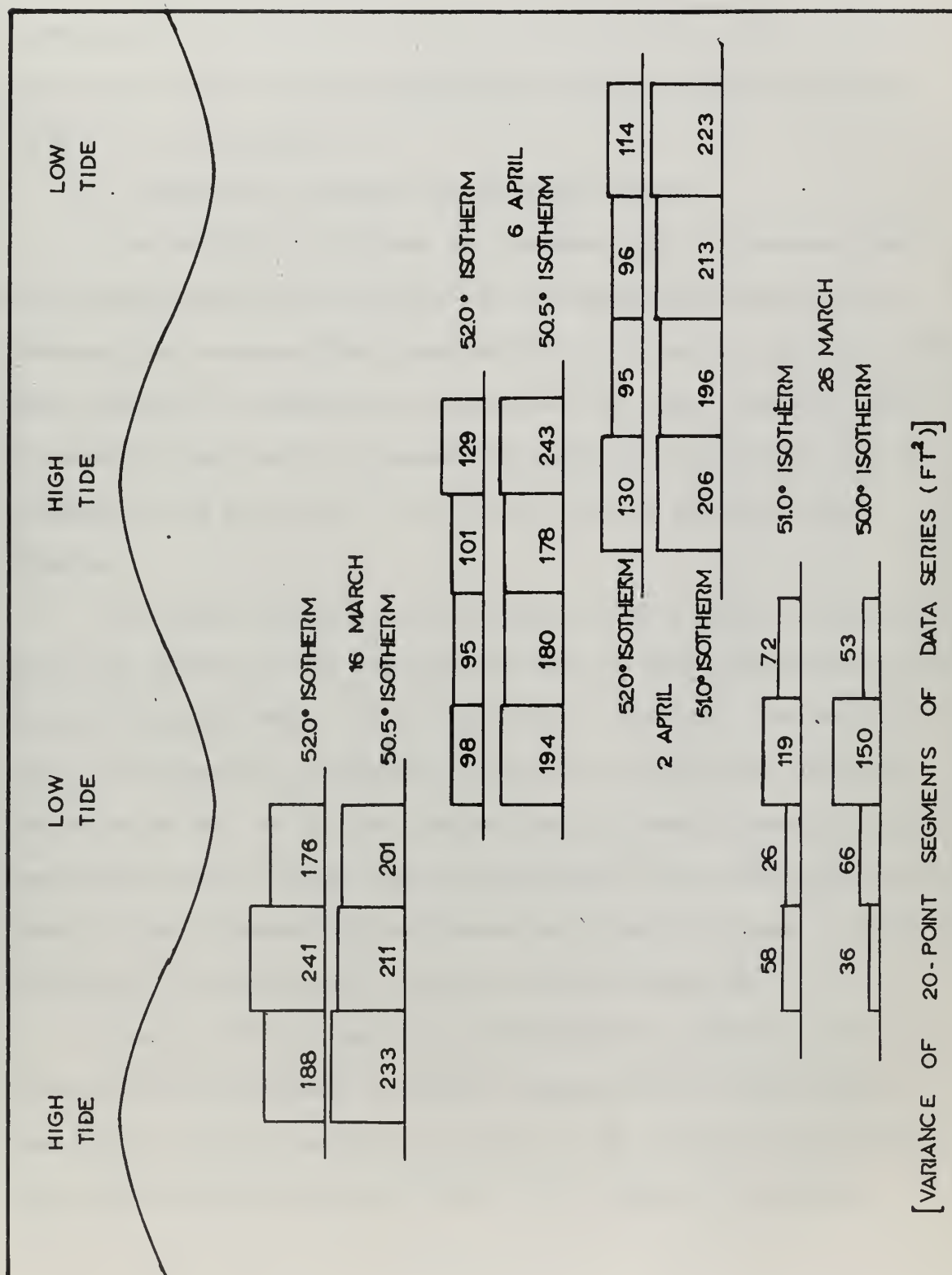
[VARIANCE OF 20-POINT SEGMENTS OF DATA SERIES (FT²)]

Figure 13

Some relationship between tide and high-frequency thermal fluctuations is suggested by this nearly consistent association of variance and tidal phase, though in some cases the maxima of variance are quite small. Knowledge of the relationship between tidal phase and tidal current in this region would allow more interesting speculation upon the causal effect of tidal currents.

    d.   Comparison of Offshore and Nearshore Spectra

       The relating of offshore and nearshore data by coherence and cross-spectra was not accomplished due to computation difficulties. Processing of nearshore data consisted merely of the calculation of the power spectrum of temperature oscillations with time. The only period of nearshore data which corresponds with offshore observation lags the offshore period by 8 hours 16 minutes and extends for 18 hours 40 minutes.

       The power spectrum of the nearshore data is shown on figure 14. The power spectrum of the offshore isotherm ($51.0^{\circ}$F) representing nearly the same relative depth is also plotted for comparison. The smoothed shape of the spectra are similar, and certain similarities in detail may be noted too. Of all the isotherm spectra from offshore data the one shown is most like the nearshore spectrum in both smoothed shape and detail. The chi-square 90% confidence limits are also shown. (Other isotherms in the same series appear in part on figure 9).

       There is little possibility that advection phenomena could account for the appearance of similar characteristics offshore and nearshore. An investigation of currents in the vicinity of the near-shore sensor (Breidenstein and Thomas [3] ) suggests that they are
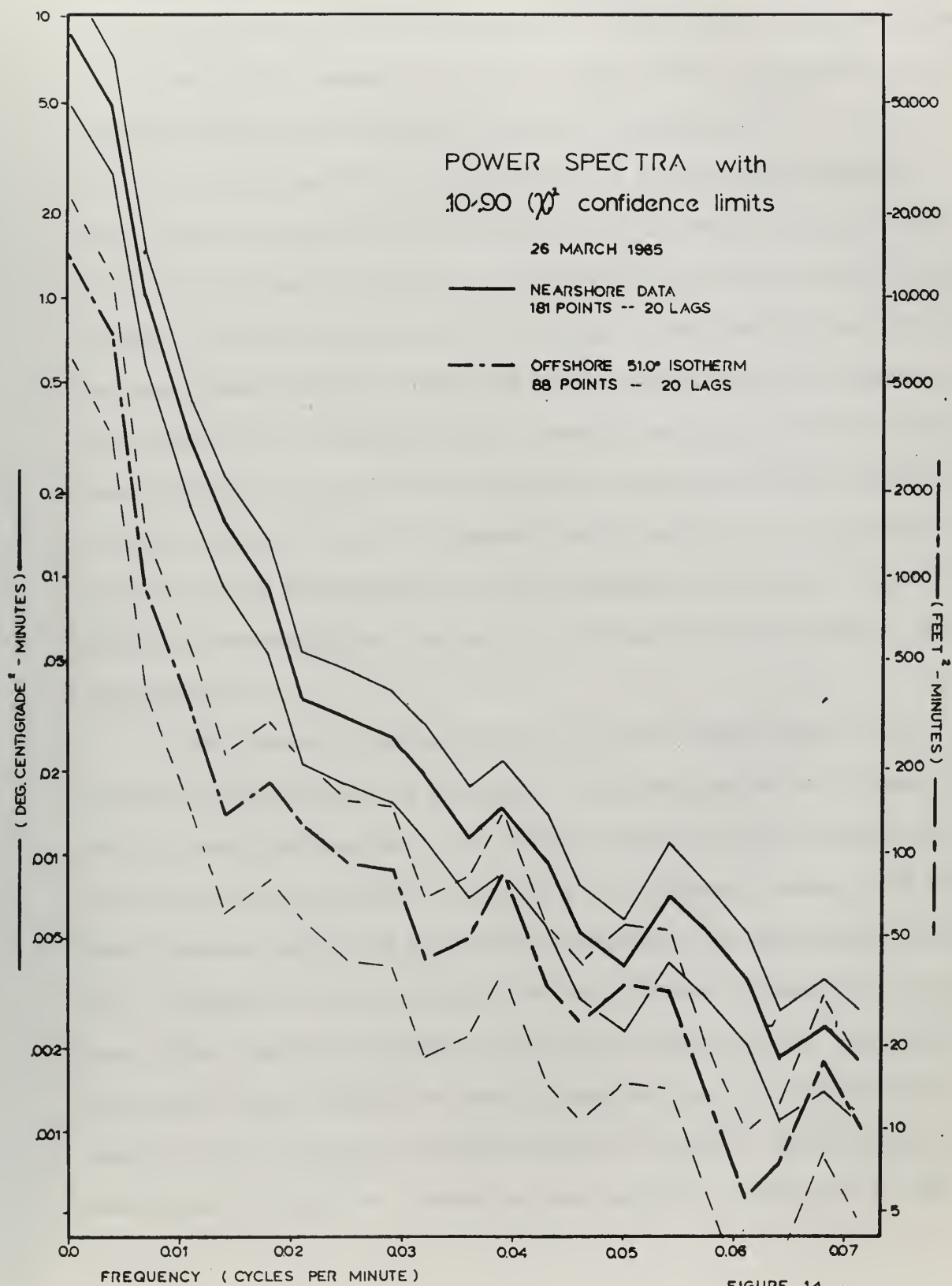
34

POWER SPECTRA with
.10‑.90 ($\chi^2$) confidence limits

26 MARCH 1965

——————— NEARSHORE DATA
181 POINTS -- 20 LAGS

—·—·—·— OFFSHORE 51.0° ISOTHERM
88 POINTS — 20 LAGS

FREQUENCY ( CYCLES PER MINUTE )

FIGURE 14

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primarily due to tides with secondary surface wind effects. It was
mentioned earlier that the temperature at 15 ft. depth nearshore varied
little, while the temperature at 8 ft. depth varied considerably; this
suggests internal waves rather than advection phenomena.

Calculation of the phase speed of a high-velocity internal
wave, using the data from the offshore site and equation (3.01), yields
0.702 meters/second (1.36 kt.). If progressive internal waves originate
offshore, then it is possible, accounting for the reduction of velocity
assuming linear shoaling, that some of the energy observed offshore is
observable in the nearshore data. Assuming that group velocity equals
phase velocity, the first of the highest velocity waves discernable in
the data (those of Nyquist frequency) would arrive, at the earliest,
5.2 hours after the beginning of the nearshore data series. Energy
observed offshore may be observable in no more than 13.5 hours of the
nearshore data.

The apparent similarity of the spectra suggests that they
represent the same type of phenomena. The same source may produce all
the perturbations observed, or a similar mechanism may be active but
in different source areas. Calculation of coherence between data from
both locations would aid in determining whether the same source produced
them. Comparison of the spectra does not indicate dispersion of energy
due to the frequency dependence of internal wave velocity. One might
anticipate some filtering of wave frequencies due to dispersion in a
single train of waves progressing shoreward from the offshore site, the
predominant frequencies depending upon the lag of observation. The

absence of filtering may suggest that internal waves are generated con-
tinuously, or that a similar generating mechanism produces the phenomenon
near both positions.

The justification for accepting or ignoring a suggestion that
offshore phenomena may be propagated or advected to a nearshore position
could be established.  Determination of the nature of the phenomena
would be necessary.  If offshore temperature data were collected simul-
taneously at three locations (triangular), then direction and speed of
propagation of the fluctuations could be calculated.  Mean current
measurements would allow discrimination between advective or internal
wave phenomena.  Such discrimination might be made by noting whether
the disturbance moved with the velocity of the current, or possibly
relative to the current with velocity consistent with that of internal
waves.  Even more detailed current observations might indicate hori-
zontal wave particle velocities (periodic currents) coherent with the
vertical motions; this would be most significant evidence of the
existence of internal waves.  Such detailed current measurements would
be difficult to make and analyse in such a spectrum of perturbations.

5. Conclusions

a. The spectral distribution offshore and nearshore appear similar in smoothed form in the one available instance of comparison.

b. A relationship between tide phase and high frequency oscillations is suggested by the increase of variance of isotherm depth immediately following the tidal extremes.

c. Spectral peaks, if real, appear to be transitory in nature both offshore and nearshore. No characteristic detail persists through all ovservations.

d. Conclusive evidence of the existence of internal waves was not shown and the progression of isotherm perturbations with the characteristics of internal waves could not be determined from the data of the two isolated observation positions.

e. Integrated spectral density appears greater in the presence of larger amplitude tidal fluctuations. No quantitative estimate is offered.

f. The application of power spectral analysis appears a promising tool in the investigation of internal wave generation relationships, but is not optimized in this project.

g. Accurate-data collection remains an unpleasant obstacle in the pursuit of oceanographic knowledge.

BIBLIOGRAPHY

1. American Philosophical Society. Hydrography of Monterey Bay, California, Thermal Conditions 1929-1933, by Tage Skogsberg. December 1936. New series, Vol. XXiX.

2. Blackman, R.R. and J. W. Tukey. The measurement of Power Spectra. Dover 1958.

3. Breidenstein, J.F. and D. M. Thomas. A Study of Water Circulation in Monterey Harbor using Rhodamine "B" Dye. M.S. Thesis. U. S. Naval Postgraduate School, Monterey, California, 1965.

4. Bulletin of Scripps Institute of Oceanography. University of California Press. Deep Sea Moorings, Design and Use with Unmanned Instrument Stations, by J. D. Isaacs, J. L. Faughn, et al. 1963, Vol. 8, No. 3, pp. 271-312.

5. Davenport, W. B., Jr., and W. L. Root. An Introduction to the Theory of Random Signals and Noise. McGraw-Hill, 1958.

6. Defant, A. Physical Oceanography, Vol. II. Pergamon Press, 1961.

7. Jenkins, G. M. General Considerations in the Analysis of Spectra. Technometrics, Vol. 2, No. 2. May 1961. pp. 133-165.

8. Lee, Owen S. Effect of an Internal Wave on Sound in the Ocean. Journal of the Acoustical Society of America, Vol. 33, No. 5, May 1961.

9. Lee, Owen S. Observations on Internal Waves in Shallow Water. Limnology and Oceanography, Vol. 6, No. 3, July 1961.

10. Pacific Naval Laboratory. The Creation and Propagation of Internal Waves, A Literature Survey,by P. A. Davis and A. M. Patterson. May 1956. Technical Memorandum 56-2.

11. Panofsky, H. S. and G. W. Brier. Some Applications of Statistics to Meteorology. Pennsylvania State University, 1958.

12. Societas Scientiarum Fennica, Commentations Physico-Mathematicae. Factors Affecting the Temperature of the Surface Layer of the Sea, by T. Laevastu. Vol. 25, 1960.

13. Tabata, S. A Study of the Main Factors Influencing the Temperature Structure and its Forecasting during the Heating Season. Journal Fisheries Research Board of Canada, 1961, (ms).

Initial test computations with large numbers of lags (as many as 50% of the number of data) were performed, resulting in some unexplained _negative_ power estimations apparently due to instability in the numerical procedures. Similar difficulty was encountered when attempting to calculate the cross-spectra and coherence of offshore and nearshore data, so results of this sort are not presented. Professor R. Read, U. S. Naval Postgraduate School Mathematics Department, believes that this unexpected result may be due to the fact that the method used in the BIMD-35 program for estimating the autocovariance function does not force the estimate to be a positive definite function. $f(p)$ is a positive definite function if for all choices of $x_1, x_2, \ldots \ldots \ldots x_n$,
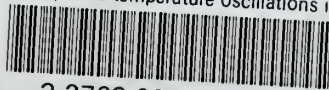
$$\sum_{j=1}^{n} \sum_{h=1}^{n} x_j \, f(j-h) x_h \geq 0$$

The number of lags employed for calculation of results shown were lower than those yielding negative spectral estimates.